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Short-range acoustic propagation under arctic ice cover during ICEX-16

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THESIS

SHORT-RANGE ACOUSTIC PROPAGATION UNDER ARCTIC ICE COVER DURING ICEX-16

by

Mitchell S. Nelson

September 2016

Thesis Advisor:	John Joseph
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SHORT-RANGE ACOUSTIC PROPAGATION UNDER ARCTIC ICE COVER DURING ICEX-16

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Submitted in partial fulfillment of the
requirements for the degree of

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from the

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ABSTRACT

During the Arctic Submarine Lab–Hosted 2016 Ice Exercise, short-range acoustic propagation under ice cover was evaluated. Sound speed profiles were measured and a series of acoustic signals at depths of 25, 50, and 183 meters and frequencies of 950, 2800, and 4050 hertz, respectively, were transmitted from the ice camp. Remotely located vertical line arrays at ranges of approximately 1.5 and 3 kilometers recorded the transmissions. The sound speed profile data obtained at the ice camp were used to model ray paths and transmission loss in the observed frequency, range, and depth combinations. The received signals were processed and analyzed to determine observed variability and transmission loss, which was then compared to the models. A key finding was the presence of a highly variable layer at 50 meters, which was characterized by its effects on sound signals and the sound speed profile. Observations also highlighted variability during transmissions and between trials while finding significant weaknesses in the modeling software's ability to accurately predict the acoustic environment in the region.

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LIST OF ACRONYMS AND ABBREVIATIONS

ASL	Arctic Submarine Lab
CTD	a device that records conductivity, temperature, and depth
G34	a high-powered projector for the mid-frequency audio range
ICEX-16	Ice Exercise, 2016
NPS	Naval Postgraduate School
NSTM	near surface temperature maximum
PSW	Pacific summer water
PWW	Pacific winter water
SL	source level
SSP	sound speed profile
SSXBT	submarine launched XBT
TL	transmission loss
VLA	vertical line array
XBT	expendable bathythermograph

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Thank you to my beautiful wife, Alana, for your continued support through this process and each trip away from home. You continue to be a great role model for our wonderful daughters, Summerlin and Everleigh, who never fail to put a smile on my face. Adventure is out there and we will continue to find it!

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I. INTRODUCTION

A. THE ARCTIC

The Arctic region is one of Earth's few remaining frontiers. Due to its isolated location, nearly uninhabitable year-round climate, and vast expanse, Arctic oceanographic research is met with many challenges (Greenert 2014). However, a different approach to Arctic expeditions was pioneered when the USS *Nautilus* cruised through the northernmost latitude while navigating under the ice-covered sea (Navy Live 2016). Today, the challenges of Arctic exploration and research have been somewhat mitigated by advances in technology for transportation, navigation, supporting infrastructure, and resupply. While submarines are likely to remain the dominant method for under-ice travel, continued Arctic exploration and research is a near-certainty based on the changing climate, affording opportunities in the region's resource abundance, trade routes, and political interests.

The current warming trends in Arctic climate change are resulting in reduced sea ice, which leads to an increase in human activities such as tourism, fishing, and resource extraction. Additionally, as the Arctic Ocean becomes a more viable route for international shipping, opportunities continue to expand for infrastructure development and commercial investment (Greenert 2014). Because of these factors, the National Science Foundation has highlighted "Navigating the New Arctic" as their fifth research idea and intends to "establish an observing network of mobile and fixed platforms to document biological, physical, and social changes, while further investing in theory, modeling, and simulation to determine regional and global effects" (American Institute of Physics 2016). In addition to scientific communities, political motivations are also highlighted by the vast expected resources.

Political and national interests are often directly associated with military implications. The strategic objectives for the Arctic Regions, as laid out in the U.S. Navy Arctic Roadmap 2014–2030, are to "ensure U.S. Arctic sovereignty and homeland defense, provide ready naval forces to respond to crises and contingencies, preserve freedom of the seas, and promote partnerships within the U.S. government and international allies" (Greenert 2014). Emphasis on a specific mission set often drives

technology to fill the operational gaps. As it relates to submarines, Rear Adm. Charles Richard, director of undersea warfare, succinctly noted, “We are constantly pushing the boundary of how to minimize our own signature—while having a better ability to detect an adversary signature” (Osborn 2016). Key to minimizing our own signature while exploiting a potential enemy, understanding acoustic propagation in the Arctic is an important component in the effective accomplishment of the U.S. Navy’s mission.

B. MOTIVATION FOR SHORT-RANGE ACOUSTIC ANALYSIS

Historically, much of the Arctic data collection was focused on long-range acoustics. The earliest Arctic acoustic studies started in the 1950s. During 1960–1965, a number of sound signals detonated at ranges out to several hundred miles from a stationary receiving hydrophone, measuring relatively low frequencies (Urick 1983). As submarines and other contacts reduce their acoustic signatures, detection ranges shrink. Additionally, high frequency acoustics has found extensive growth in specialized applications such as mapping topography, small object detection, and under ice navigation (Cox 2004). Thus, it has become increasingly important to understand acoustic propagation over shorter ranges and higher frequencies, while validating the performance and tactical relevancy of the current models in use.

The accuracy of models and simulations are dependent upon the accuracy of the data inputs used for analysis. A key component for modeling acoustic propagation through a body of water is the sound speed profile (SSP). An indication that Arctic acoustics should be revisited is highlighted in Figure 1, which shows the SSP generated from the climatography database used for tactical decision aids vs. a SSP obtained from an Ice Tethered Profiler (ITP) near the same area within the last year (Woods Hole Oceanographic Institute [WHOI] 2015). Deviations between the two profiles in Figure 1 are immediately apparent, particularly the sound speed peak observed from the ITP at approximately 60 meters. Because predictive modeling software relies on accurate sound speed profiles, any differences between the two profiles can result in significant inconsistencies in the propagation models, changing the tactics used to exploit the ocean environment.

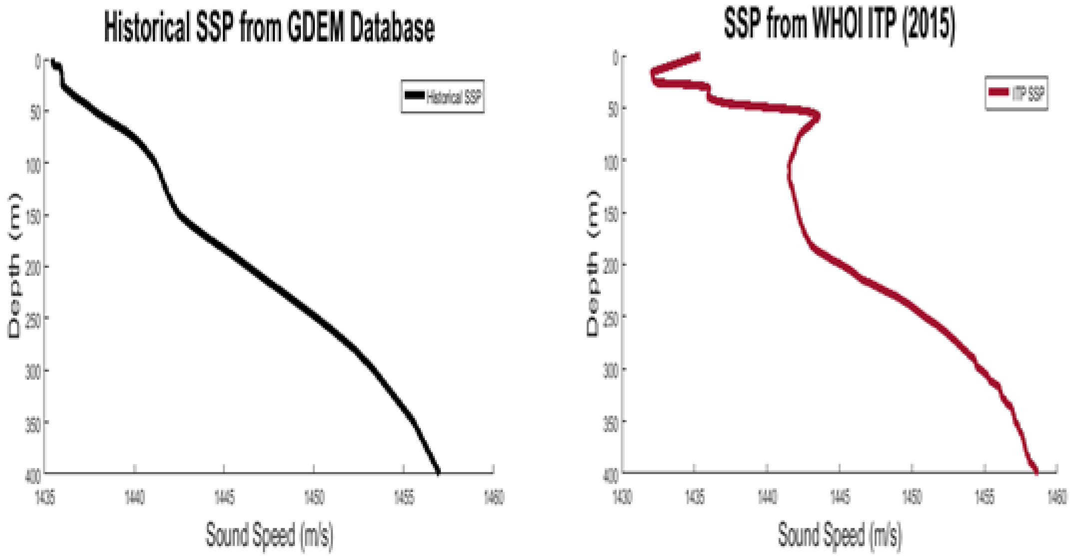

Figure 1. Differences Between Database SSP and Recent ITP SSP. Source: WHOI (2015).

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II. BACKGROUND/ THEORY

A. THE BEAUFORT SEA

The particular region of the Arctic where this experiment was conducted is the Beaufort Sea, which encompasses the water mass north of Alaska and Canada. The Beaufort Sea has a surface area of 476,000 square kilometers and an average depth of about 1000 meters (Britannica 2016). Ice circulation in the Beaufort Sea is primarily a function of the wind-driven average high pressure system over the region, resulting in a clockwise ocean circulation pattern known as the Beaufort Gyre. Sea ice trapped in the Beaufort Gyre may circulate around the Arctic for several years, resulting in increased incidences of sea ice bumping into one another. These effects combined with the extended length of time ice remains trapped in the gyre results in thicker sea ice in the Beaufort Sea than in other regions (National Snow & Ice Data Center 2016). Circulation patterns also include relatively warm Pacific water entering the Arctic from the Chukchi Sea, through the Bering Strait. This layer of water is subducted beneath the less saline surface layer of melted ice and results in a shallow temperature maximum, commonly referred to as Pacific summer water (Steele 2004). The combined effects of ocean circulation, sea ice composition, and stratified water masses play a critical role in the short range acoustic propagation.

B. ACOUSTICS FUNDAMENTALS

A brief overview of ocean acoustic fundamentals is useful for interpreting the presented data, and characterizing the significance of observed effects on the findings.

1. The Sonar Equations

A basic understanding of transmitted and received acoustic signals is best represented by the sonar equations. The sonar equations were developed during World War II as the basis for calculating the expected initial detection ranges of contacts for sonar equipment, and for determining sonar performance and design capabilities (Urick

1983). Equations exist for both active and passive sonar, but only the passive sonar equation is applicable to this source-receiver combination:

$$SL - TL = NL - DI - DT$$

The acoustic source is represented as SL for source level, which refers to the level of radiated sound intensity, referenced from a distance of 1 meter. As the radiated sound travels to the receiver, it’s level is reduced by the transmission loss, TL. Assuming the background noise is isotropic, we define the background level as simply NL, as described by Urick (1983). Urick further explains that the directivity index, DI, lowers the NL, such that the relative noise power is NL-DI. Lastly, the detection threshold, DT, is the minimum received level that the system can distinguish for a given probability of detection and false alarm rate (Urick 1983).

2. Spherical Spreading

Acoustic propagation in the sea is affected by an incredibly complex system of dynamic effects and boundaries. As discussed by Urick (1983), the reduction in sound intensity between a reference point 1m from the source to a point some distance away is called transmission loss, TL, and may be considered to be the sum of spreading and attenuation losses. Urick further describes spreading loss as “a geometrical effect representing the regular weakening of a sound signal as it spreads outward from the source” (Urick 1983). For the purposes of this experiment, short ranges over a deep ocean bottom, a spherical spreading model is adequate to describe the general characteristic of spreading losses. In an iso-speed environment, the acoustic energy from the source is transmitted equally in all directions, representing an expanding sphere of sound emanating from the source. The spherical spreading loss model is characterized by the following equation, where r represents the distance from the source. (Urick 1983):

$$TL = 20\log(r).$$

3. Absorption

Absorption is a form of attenuation that involves the direct conversion of acoustic energy into heat (Urick 1983). As described by Urick, absorption is a fairly complex process, characterized by effects of frequency, depth, pH, and other factors on the molecular level of the medium. The effects of absorption are a contributing factor in the reduction of sound pressure from source to receiver and is accounted for in the calculation of transmission loss in this set of observations.

4. The Speed of Sound in Water

A critical component for modeling sound propagation through the ocean is the speed of sound through the medium, which is represented by the water column's sound speed profile. The sound speed is characterized by the temperature, salinity, and pressure for a particular point in the water column, and sound speed increases with an increase in any of the parameters (Urick 1983). Noted by Urick (1983), "strangely enough, no other physical properties have been found to affect the velocity of sound in seawater, with the exception of contaminants such as air bubbles and biological organisms." In this experiment, the sound speed profiles were obtained with field observations using an instrument commonly referred to as a CTD (conductivity, temperature, and depth). CTDs measure each of the listed parameters when lowered in the water column and reeled back up, collecting data on both the "down-cast" and the "up-cast." The collected data is then used to calculate the sound speed profile for that location at that point in time. A field expedient alternative for determining the sound speed profile utilizes an expendable bathythermograph (XBT), which obtains only the temperature profile without having to retrieve the sensing unit. Operationally, submarines deploy a version referred to as an SSXBT for collecting data to exploit the tactical environment.

5. Sound Speed Gradient

Sound speed gradients are formed by variations in temperature, salinity, and depth. The result is a non-uniform sound speed throughout the column of water. If the water column is divided into horizontal layers of uniform sound speed, the acoustic propagation can be modeled from one layer to another, using Snell's law. Snell's law is:

$$\frac{\cos\theta_1}{c_1} = \frac{\cos\theta_2}{c_2} = \frac{\cos\theta_3}{c_3} = ... = \textit{constant for any one ray,}$$

where θ represents the angle with respect to the horizontal and c is the sound speed for that layer of water in the column (Urick 1983). The process of refraction can result in wildly varying acoustic propagation paths through the ocean.

As sound travels through the water, refractions will occur with relation to the SSP. Eventually, the sound will be reflected off an object or fluid interface, or is trapped in in a sound channel. A sound channel refers to a location in the water column where the acoustic transmission is bounded by a downward refracting layer of water above, and an upward refracting layer below (Urick 1983). Sound channels result in acoustic signals being trapped in the channel and traveling longer ranges with less transmission loss. These effects also extend to examples of sound being reflected from the surface and refracted back up, or any other imaginable combination.

The ocean surface has a significant effect on relatively shallow water acoustic propagation, as it acts to both scatter and reflect the sound energy (Urick 1983). Analysis of recent sound speed profiles in the region reveals that surface reflection from ice coverage is expected to play a critical role in the short-range, shallow sound propagation evaluated in this experiment. Bottom reflections are not expected to have a measurable impact on observed acoustic propagation due to the deep ocean basin and upward refracting environment encountered in the region.

6. Ray Theory

Because sound does not typically travel in straight lines through the water, the possible acoustic paths are often modeled using rays, which characterize the propagation of the local wave front. As described by Urick (1983), “ray theory represents the sound field as a sum of ray contributions with each ray emanating from the source or its image in the reflections from surface and bottom. The transmission loss between the source and any point in a ray diagram may be readily found in terms of the vertical spacing between rays that are adjacent at the source and pass above and below the receiver.” At a point P

representing the receiver, the sound pressure is represented as the sum of all contributing ray vectors, and can be written as:

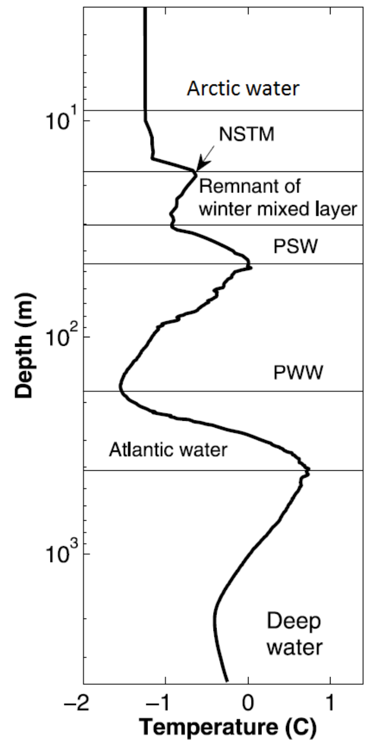
$$P = \rho_o \sum_{m=0}^{\infty} \frac{R_m e^{ikr_m}}{r_m},$$

where ρ_o = source pressure, r_m = distance of nth image from P , R_m = amplitude reflection coefficient appropriate for nth image, and k =wave number equal to $2\pi / \lambda$ (Urick 1983). An evaluation of ray theory can also indicate potential shadow zones, where the acoustic paths are not expected to travel and detection of the source signal is expected to be low (Urick 1983).

C. ARCTIC OCEANOGRAPHIC PROCESSES

1. Seasonal Cycles

Sound speed profiles in the Arctic are influenced by seasonal cycles, which affect temperature and salinity distributions through mechanical processes. These mechanical processes include seasonal attributes, river influxes, precipitation, tidal mixing, and convection. Seasonal attributes encompass the freezing of ocean water into ice, which releases cold salty brine, as well as the melting of ice, resulting in the addition of fresh water to the mixed layer (Cole et al. 2014). The layer containing these seasonal variations is termed “Arctic Water” and extends to a depth of about 60 meters (Milne 1967). The bottom of this layer typically results in near surface temperature maximum (NSTM), above which surface ducting occurs (Jackson et al. 2010). Below the NSTM are two layers of seasonal Pacific water masses, the Pacific summer water (PSW) and the Pacific winter water (PWW), respectively. The layer immediately below is called “Atlantic Water” and extends to a depth up to around 900 meters (Milne 1967). The water mass below this layer is generally called deep water (Jackson et al. 2010). A general illustration of water layers in the Canada Basin of the Beaufort Sea is provided in Figure 2. These layers are generally stratified based upon density factors of temperature and salinity. Typically, water that is cold and saline sinks to the bottom and warm and fresh water will rise to the top, however this is not always the case.



This profile illustrates the general composition of layered water masses in the Canada Basin of the Beaufort Sea. Note that this figure incorporates some measures which may be only seasonally observed. NSTM refers to the near surface temperature maximum, while Pacific summer water and Pacific winter water are abbreviated PSW and PWW, respectively.

Figure 2. Water Mass Layers in the Canada Basin of the Beaufort Sea. Adapted from Jackson et al. (2010).

2. Spice

The mixing of two different water masses can result in an ocean phenomenon known as "spice." Spiciness in the Arctic can specifically refer to the occurrences of the Arctic mixed layer and PSW waters combining in such a way that "warm and salty" or "cold and fresh" regions form in the water column, resulting in unexpected acoustic propagation characteristics. Because of a density equilibrium resulting from competing effects of temperature or salinity, abnormal stratification can occur with colder water over warmer water, or more saline water on top of relatively fresher water. The combination of warmer and saltier water results in higher sound speed profiles at those

locations. Stratification in the mixed layer is largely affected the properties that cause mixing.

3. Turbulence

The same processes that result in ice melt, vertical convection and absorption of solar radiation, also aid mixing in the water column. These processes result in positive and negative temperature gradients, which drive fluid motion in the vertical water column. Additionally, wind forcing on the sea ice creates ice motion, resulting in ice-ocean velocity and shear, thereby forcing ocean currents and internal waves. These upper ocean processes are largely affected by the total amount of ice coverage and will continue to change as total ice coverage continues to decline.

Ice cover appears to have a dampening effect on vertical mixing rate due to weakened internal wave activity (Cole et al. 2014). The combination of inertial and tidal motions make up the largest portion of the internal wave field, however disruption of the mixed layer is also affected by eddies and turbulent motion as a result of drag between the ice and ocean. Previous research revealed mixing was enhanced by Ekman-like shear in the mixed layer, inertial and tidal currents throughout the water column, and weak geostrophic velocities (Cole et al. 2014). These factors and others result in conditions that make broadly characterizing all under-ice oceanographic acoustics a challenge.

4. Under Ice Topography

Under ice topography is an important consideration for acoustic propagation in the Arctic. Underside roughness of the sea-ice becomes an important factor for long range sound propagation, as it directly affects the scattering properties at the upper boundary and the effects are compounded for each reflection. The roughness and reflectivity of the underside of the ice controls the propagation loss at the water-ice interface. Specifically, the reflectivity is affected by entrained bubbles and the crystalline structure of the skeletal freshwater ice as brine is rejected during the process of freezing, and is thus affected by seasonal variations (Milne 1967).

The purpose of this analysis is to gain a better understanding of short range Arctic acoustics in consideration of all the aforementioned variability effects and to evaluate our current model predictions against real world observations. With the exception of normal effects such as rafting and leads, the under-ice composition in this experiment is considered to be as static as reasonably achievable, given fixed points for source and receiver locations. Due to the short duration of data collection, no seasonal variations are expected. Additionally, geographical expanse is limited to the ice floe drift over a flat portion of the Beaufort Sea deep basin. Therefore, minimal changes in ocean floor topography are expected.

III. EXPERIMENTAL SET UP

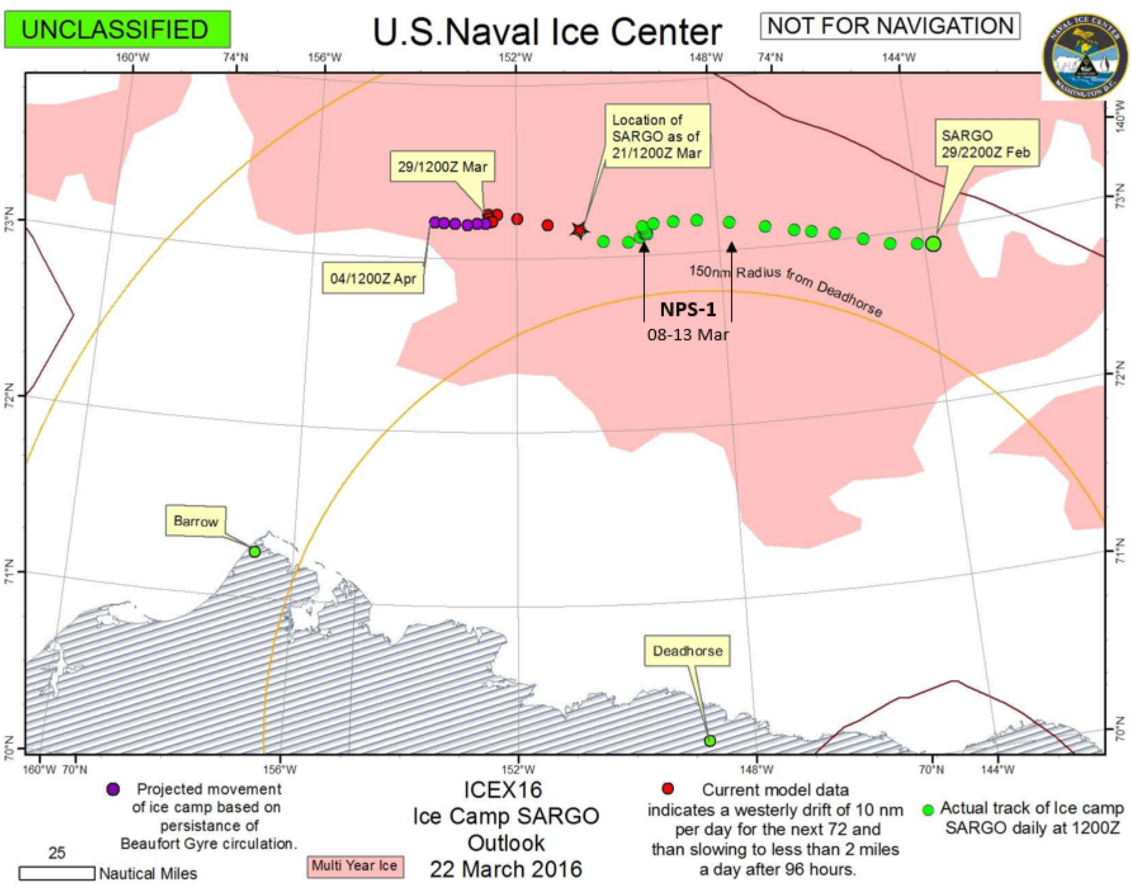
A. ICEX-16

Research was conducted through participation in the U.S. Navy's arctic exercise and research program, Ice Exercise 2016 (ICEX-16). The Navy's Arctic Submarine Lab (ASL) is the lead organization for coordinating the program on an approximate bi-annual schedule. As stated on their webpage, the ASL is "responsible for developing and maintaining expertise in Arctic specific skills, knowledge, equipment and procedures to enable the submarine force to safely and effectively operate in the unique Arctic Ocean environment (ASL 2016)." The United States Navy (2016) described ICEX-16 as an exercise in the Arctic which enabled scientific research and operational testing and evaluation of capabilities, and included the participation of two submarines, four nations, and over 200 personnel.

According the Navy's Arctic Road Map 2014–2030, "the Navy will continue to learn more about the evolving operating environment through exercises such as ICEX" (Greenert 2014). The remotely located research station was called Ice Camp Sargo, named after the submarine (SSN-588), and served as a temporary command center for conducting operations. The logistics headquarters was located in Prudhoe Bay, Alaska, where the arrival of teams and associated equipment to the remote location was phased in order to optimize Camp Sargo's limited occupancy capacity, while de-conflicting the timeline for interfering projects. Small aircraft shuttled personnel back and forth, covering approximately 300 kilometers across the Beaufort Sea each way. An incredible amount of logistical planning was coordinated to meet the camp's infrastructure requirements.

Camp Sargo's signature central command dome was utilized for general operations coordination. Key features of the ice camp also included a large messing tent and the required amount of birthing to support the camps design occupancy for both research and support personnel. Several insulated tents were allocated for conducting research and storing associated equipment. The research data collected in this experiment

occurred during the first increment of the phased research cycles and is represented by the NPS-1 bracketed area shown in Figure 3, which also illustrates the ice floe motion. Physical changes in the ice floe were characterized by incidences of rafting and the formation of ice leads. Unfortunately, an ice lead propagated through the ice camp, and resulted in an immediate evacuation before the fifth and final week of research operations.



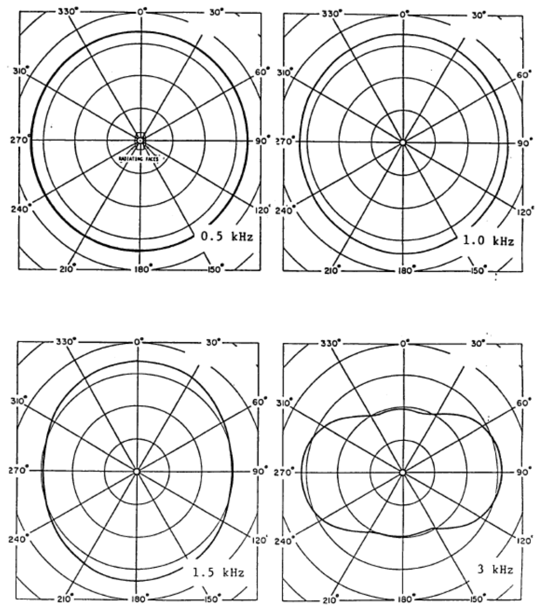
The observations collected in this experiment occurred over the "NPS-1" bracketed area, indicating initial ice floe movement of approximately 20 nautical miles westward per day and slowing to near zero at the conclusion.

Figure 3. Ice Floe Drift During ICEX-16. Adapted from Naval Ice Center Map.

B. EQUIPMENT

This experiment utilized five acoustic recorders: two recorders for each vertical line array, and one used as an acoustic reference near the source. Green Ridge Science manufactures the instruments and describe the Acousonde recorders as miniature, self-contained, autonomous acoustic/ultrasonic recorders designed for underwater applications. The Acousonde recorders are powered by lithium batteries, are fully sealed, programmable, and are designed for applications ranging from field recorders to marine wildlife tagging. Due to concerns about extremely low ambient air temperatures, the Acousonde recorders were carefully insulated up to the point of deployment into the water. No recording equipment malfunctions or damage due to Arctic exposure were observed in the data sets.

The acoustic source was a Navy Type G34 projector. The G34 is a high power projector, using a multi-tonpilz design with seven stacks of PZT disks collectively loaded on both ends with metal plates, yielding a frequency range of 200–5,000 hertz. While generally considered an omni-directional source, there is some slight directionality at the projectors upper frequency outputs, shown in Figure 4. The G34 was raised and lowered in the water column using an electric winch outfitted with a mono-filament coaxial wire for acoustic source operation. MATLAB was used to program the transmission sequence to the source amplifier cabinet.



Generally considered omni-directional, the Type G34 Projector exhibits some directionality at higher frequencies.

Figure 4. Typical Patterns for the Type G34 Projector. Source: Type G34 Transducer Technical Manual.

The conductivity, temperature, and depth profiles obtained at the source location were acquired using a Sea-Bird Electronics SBE 19 CTD profiler. The instrument was moved in the water column using a hand operated winch wound with nylon rope. The SBE 19 did not utilize a pumping feature for continuous forced water injection during operation. Thus, flow through the CTD was the result of vertical movement through the water column. Due to extreme low temperatures experienced at the location, the instrument was stored in the water column at a depth of approximately 2 meters when not in use to prevent freezing of the flow port.

C. CONFIGURATION

The experiment configuration consisted of a source station, located at Camp Sargo, and two remote vertical line array stations located 1.25 and 2.83 kilometers away, positioned in nearly opposite directions with 160 degrees of separation referenced from the source location. GPS tracking devices were placed at each location to accurately monitor ice floe drift and relative movement between source and receivers. The source

station was established inside of a heated tent, and consisted of the source winch and a wooden A-frame suspension system to support the G34 sound source and the Seabird 19 profiling CTD into the water column through a hole in the ice. Electrical power was supplied via portable generators.

The remote locations were accessed via snowmobile and were built from angled steel stock to support the vertical line arrays. The VLAs were configured with nylon rope, and Acousonde recorders at depths of 30 meters and 183 meters to capture acoustic transmissions above and below the anticipated sound velocity peak at 50 meters. All recorders were collected at the conclusion of the experiment, and detailed processing and analysis was completed at the Naval Postgraduate School.

D. PROCESSING TOOLS/ ANALYTIC METHOD

The modeling tool Bellhop was used in Matlab software to develop the acoustic models. Beginning with the seven “up-cast” CTD profiles, an average sound speed profile was obtained to characterize the region of water. In addition, sound speed profiles were generated to represent plus and minus two standard deviations from the mean in order to approximate expected variability. Using these profiles, ray paths were evaluated to understand the expected propagation paths, and transmission loss profiles were generated. Received acoustic levels from the Acousonde recorders were processed and analyzed to assess variability and determine transmission loss for each trial scenario. The observations were then compared to the modeled results for consistency.

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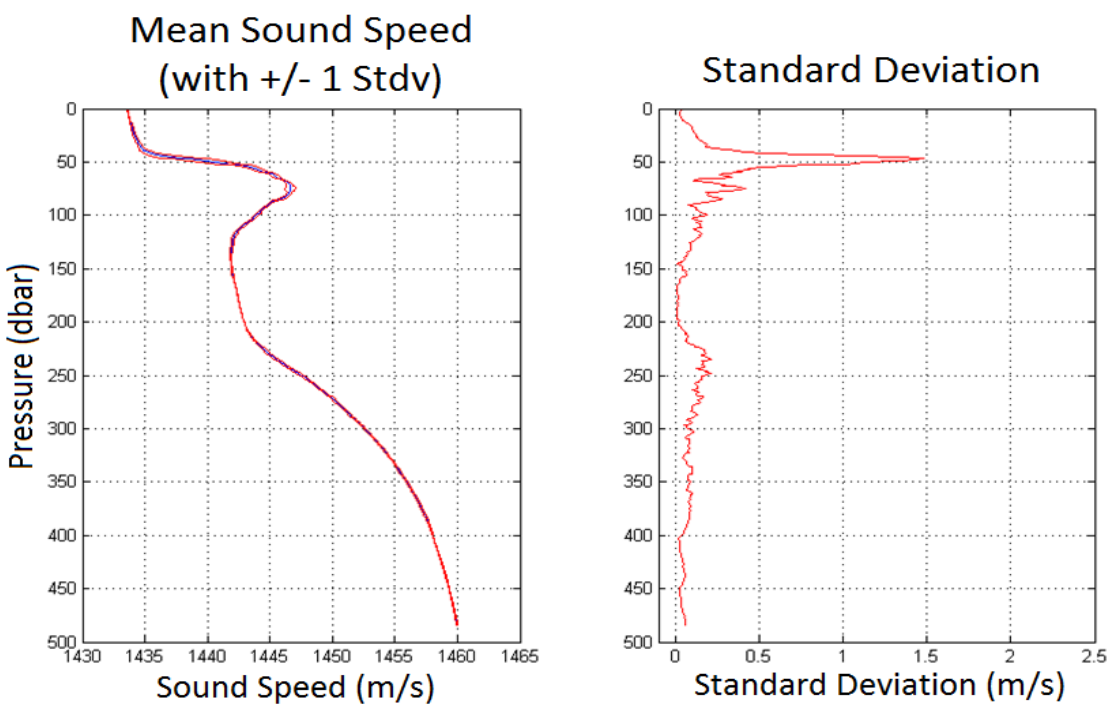
IV. DATA ANALYSIS

A. SOUND SPEED PROFILES

A total of seven CTD casts were performed. The CTDs collect data on both the downward travel and the upward travel, so it is possible to collect two data sets for each cast. Because the CTD recorder was stowed at a shallow depth during periods between casts, only travel in the upward direction was analyzed in order to minimize anomalies due to potentially frozen orifices on the down-cast. Although the geographical location of the ice floe drifted up to 30 kilometers per day as shown in Figure 3, the general form of the sound speed profile remained very consistent across the seven CTD casts. The major variation between casts consistently occurred at approximately 50 meters, as demonstrated in Figure 5.



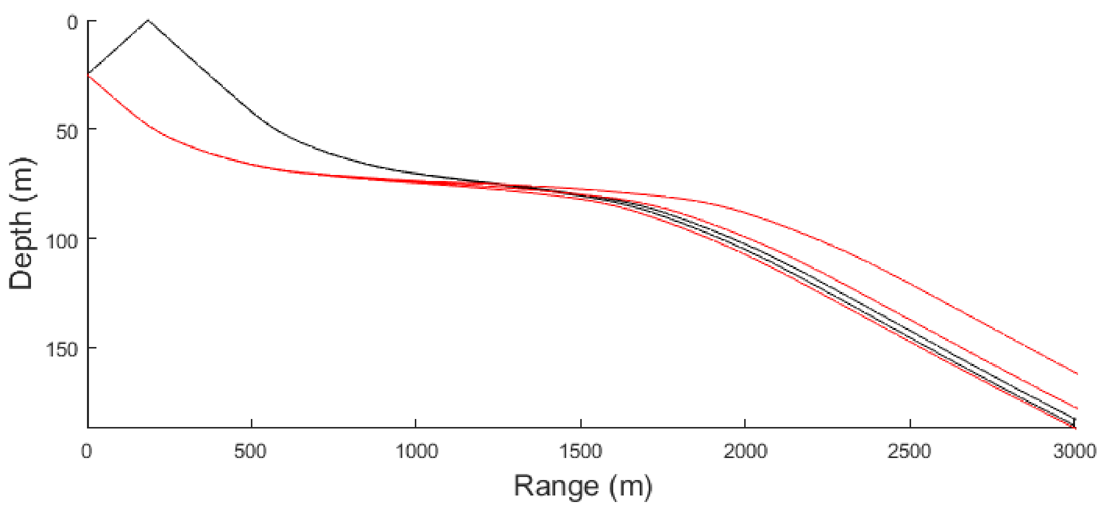
The graph on the left represents the mean sound speed profile in blue and +/- 1 standard deviation from the 7 CTD casts shown in red. The graph on the right highlights the variability identified at 50 meters.

Figure 5. Comparison of Sound Speed Profiles with Standard Deviation

B. MODELING AND SIMULATION

1. Ray Paths

The sound speed profiles were used to create models of the ray paths, to gain an understanding of how the sound is anticipated to travel through the water. The surface was modeled as planar and the bottom was modeled as an acoustic half-space with a compressional sound speed of 1520 meters/second, density of 1.421 grams/cubic-centimeter, and attenuation of 0.152 decibels/wavelength (Hamilton 1980). It is of particular interest to characterize the paths through water column across the area of largest variability, at 50 meters. The expected acoustic path for a transmission at 25 meters to a receiver at 183 meters is shown in Figure 6.



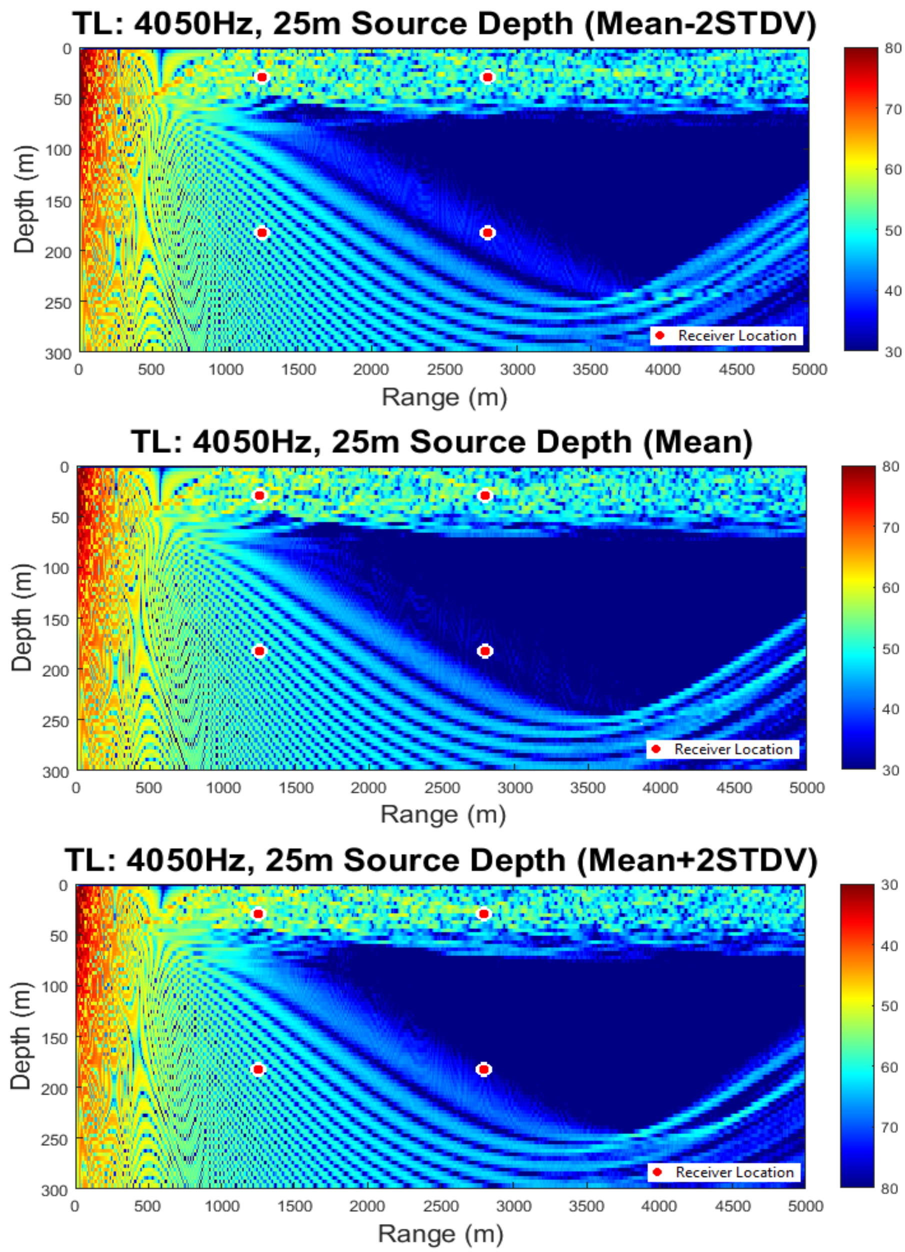
This figure shows the acoustic ray trace for a source at 25 meters and a receiver at 183 meters.

Figure 6. Acoustic Ray Path Across Sound Speed Peak

2. Transmission Loss Variability from the Mean

Coherent transmission loss was modeled to represent acoustic propagation path for each source and receiver depth combination. The mean sound speed profile was calculated and two additional reference sound speed profiles were generated by adding and substracting two standard deviations of sound speed variability from the mean, which highlight possible variations in transmission loss due to fluctuations in the SSP. An

example of coherent transmission loss variability for a 4050 hertz signal transmitted at 25 meters is shown in Figure 7. While variations from the mean are noticeable, they were generally much less profound than other characteristics investigated through modeling.

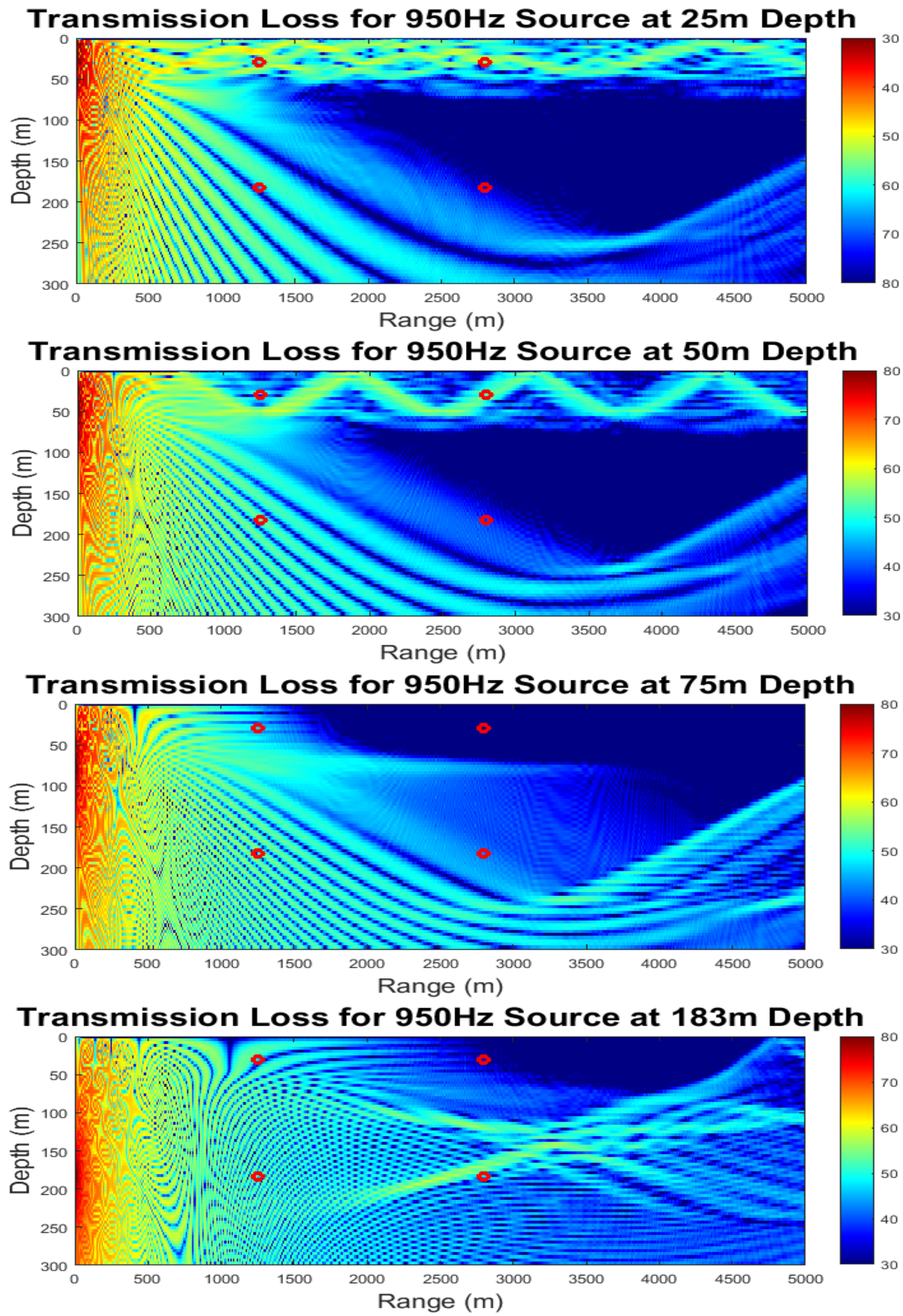


The effects of sound speed variability on transmission loss are shown by generated models of the mean and the mean +/-2 standard deviations of observed sound speed variability. The four receiver locations are shown for reference comparison.

Figure 7. Effects of Sound Speed Variability on Transmission Loss.

3. Transmission Loss Variability with Depth

Transmission loss was evaluated using the mean sound speed profile in several depth increments to identify expected variability across relevant portions of the water column. Significant changes can be identified in transmission loss models over relatively small changes in water depth, as shown in Figure 8. The sound speed peak at approximately 80 meters resulted in a sound channel near the surface boundary and greatly impacted the acoustic paths in the shallow portions of the water column. Based on these observations, small changes in depth near the shallow sound speed peak would be expected to result in large changes in transmission loss.



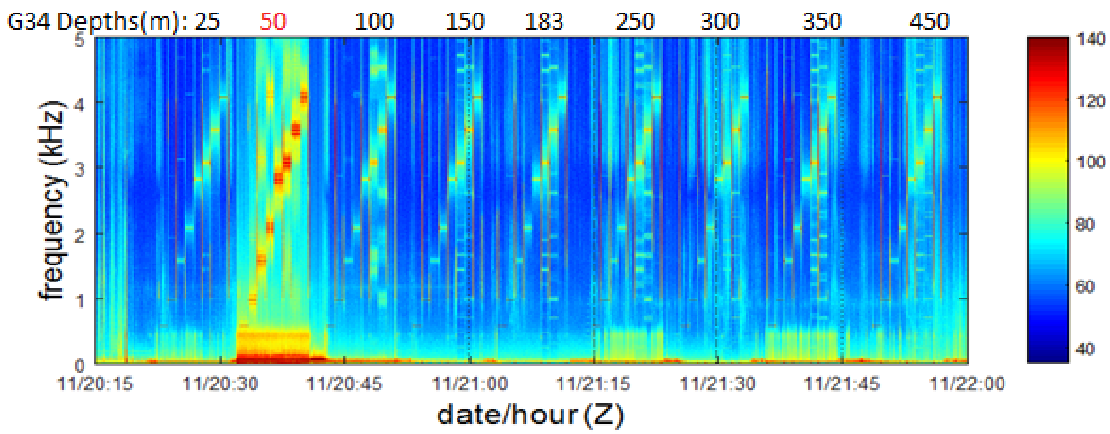
This series of models illustrates the effects of depth variability on transmission loss.

Figure 8. Transmission Loss Variability with Depth.

C. TRANSMISSION LOSS CALCULATIONS

1. Source Levels

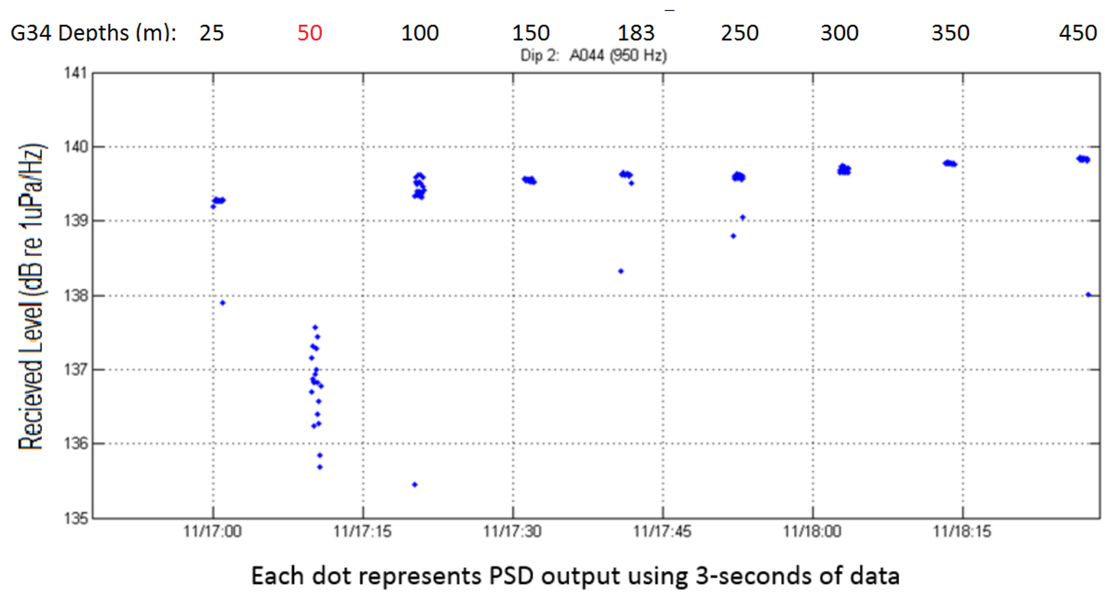
The reference detector, located 5 meters below the source, was evaluated to determine the output consistency of the Navy Type G34 projector. In nearly all cases, the source maintained a steady output within a fraction of a decibel over the 57 second duration of sound transmission. When comparing source sound levels between the four different trials, an interesting phenomenon was identified when the source was transmitting at 50 meters' depth. A spectrogram identifying acoustic energy across the frequency spectrum is shown in Figure 9, highlights the broad amount of energy across the frequency spectrum observed when transmitting at 50m as compared to other transmission depths, which may be self-noise caused by turbulent flow around the receiver. Based on the performance at all other depths, the source is believed to have been operating properly, and the unexpected indications are a result of oceanographic features and acoustic scattering properties.



This spectrogram shows the entire range of frequencies and depths transmitted. Notice the broad frequency spectrums occurring at the 50 meter transmission depth, which may be due to turbulent flow around the receiver.

Figure 9. Spectrogram for Monitoring Hydrophone During Transmission.

Additionally, the decibel levels recorded from the reference detector 5 meters below the projector were evaluated for output consistency at each transmission depth. The 57 second transmission was integrated over 3 second-averaged intervals, and each of the averaged intervals are identified in Figure 10. The results indicate the source transmissions at 50 meters had much more variability than was observed at other depths.



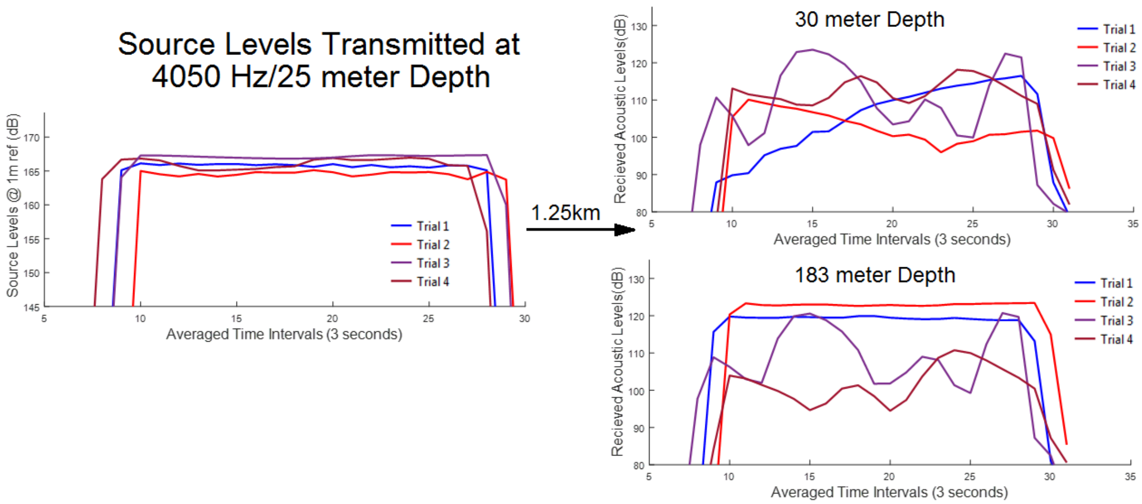
This illustrates the dispersion of received 3-second average acoustic levels measured at the source reference detector 5 meters below the projector. Notice the spread of received signals at the source level of 50 meters.

Figure 10. Measured Source Reference Signals at 950 Hz.

2. Received Levels

The four Acousonde acoustic recorders were analyzed for variation during and between acoustic transmission. On several occasions, received acoustic levels for a given depth, range, and frequency had significant variations when compared to other transmissions recorded in the same configuration, but during a different trial run. In some cases, 15–20 decibel outliers were observed between trials. Another key observation was the variability observed during transmission periods. Received signal fluctuations on the order of 10 decibel or more were frequently observed during the 57 second acoustic transmission periods. On most occasions, these highly fluctuating received signals were

obtained without observing noticeable fluctuations on the reference detector. However, minor fluctuations observed at the reference detector typically translated into much larger variations at the VLA stations. Typically, the received acoustic variation effects were most prominent when the source was transmitting at 50 meter depths. An example of high fluctuations observed in received acoustic levels is shown in Figure 11.



This is an extreme example of observed variability during the 57 second transmission periods. Also note the relatively steady output signal from the source, and the amount of variability between the 4 trial runs. In most cases, the monitoring hydrophone acoustic signals were represented by a flat line.

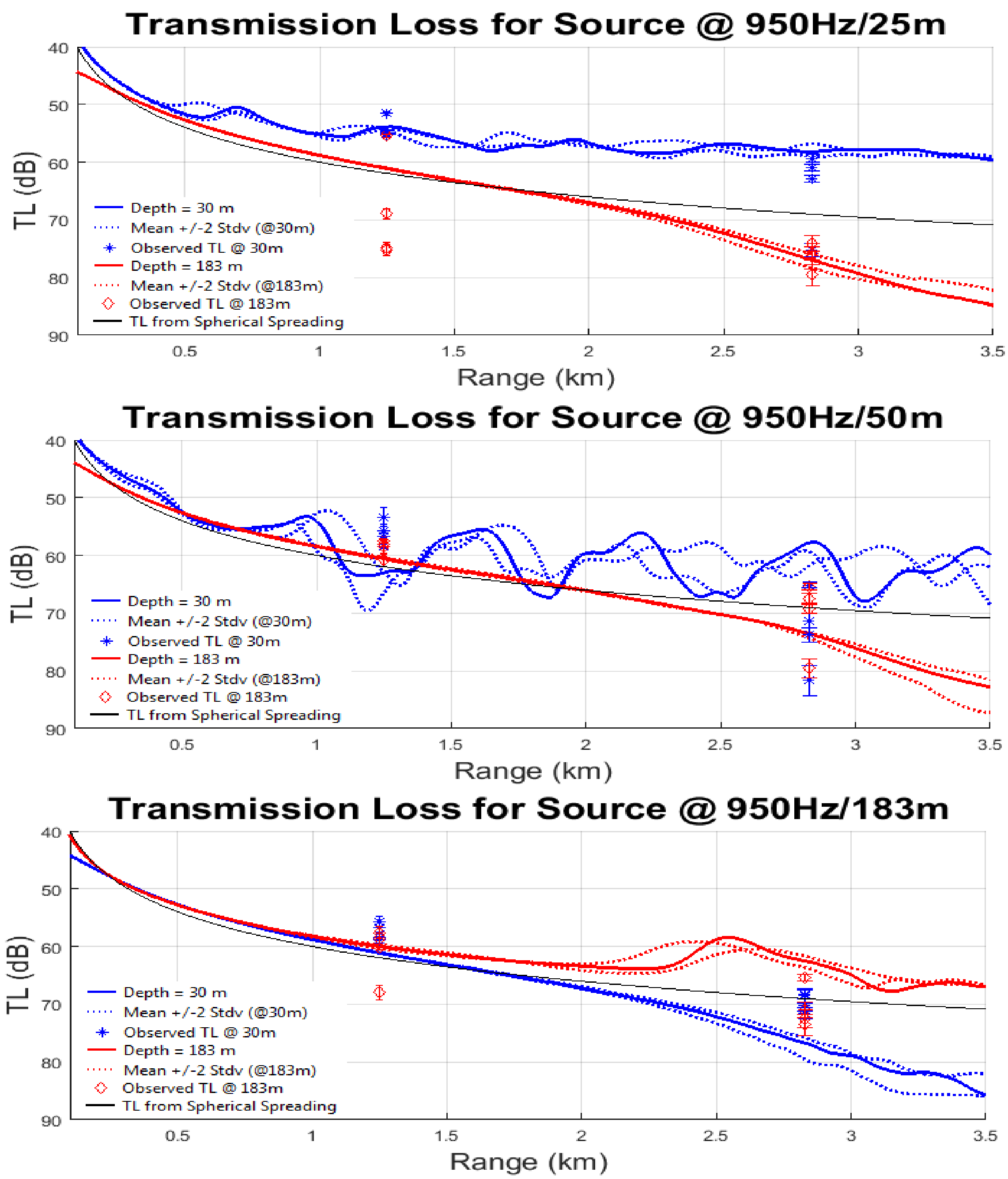
Figure 11. Source to Receiver Acoustic Variability

3. Transmission Loss

The three-second averaged intervals for Source and receiver sound pressure levels were averaged over the transmission interval to obtain single values for the source and received levels used in transmission loss calculations. Source levels were corrected to a 1-meter reference, using a spherical spreading model. In instances of abnormal acoustic scattering, as identified in Figure 10, the source levels were individually corrected to approximate the actual sound pressures expected from the G34 source in those cases. The approximations were based on observed operating characteristics, taking into account the values observed at depths above and below, and are expected to approximate the actual

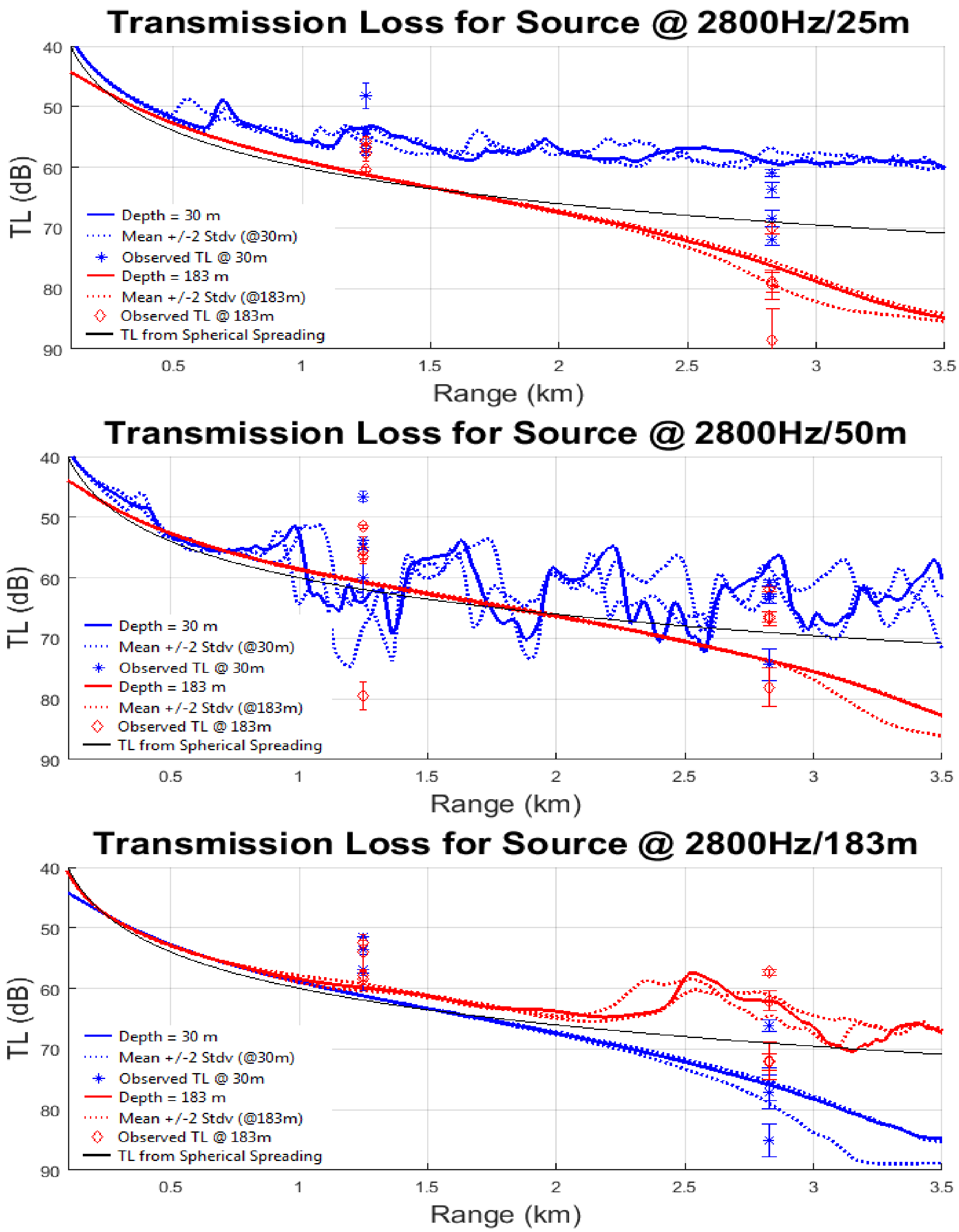
projector output within 0.5 decibels. Transmission loss was then found by subtracting the received signal levels from the associated source levels.

Observed transmission loss for each source and receiver combination are provided in Figures 12–14, with curves indicating modeled incoherent transmission loss. The modeled data also include dotted lines indicating +/- 2 standard deviations from the mean sound speed profile for visual representation of possible variability. Transmission loss markers include 1 standard deviation error bars to highlight the level of variability in received sound pressure levels over each 57-second transmission. A curve representing the expected transmission loss resulting from spherical spreading is provided for reference.



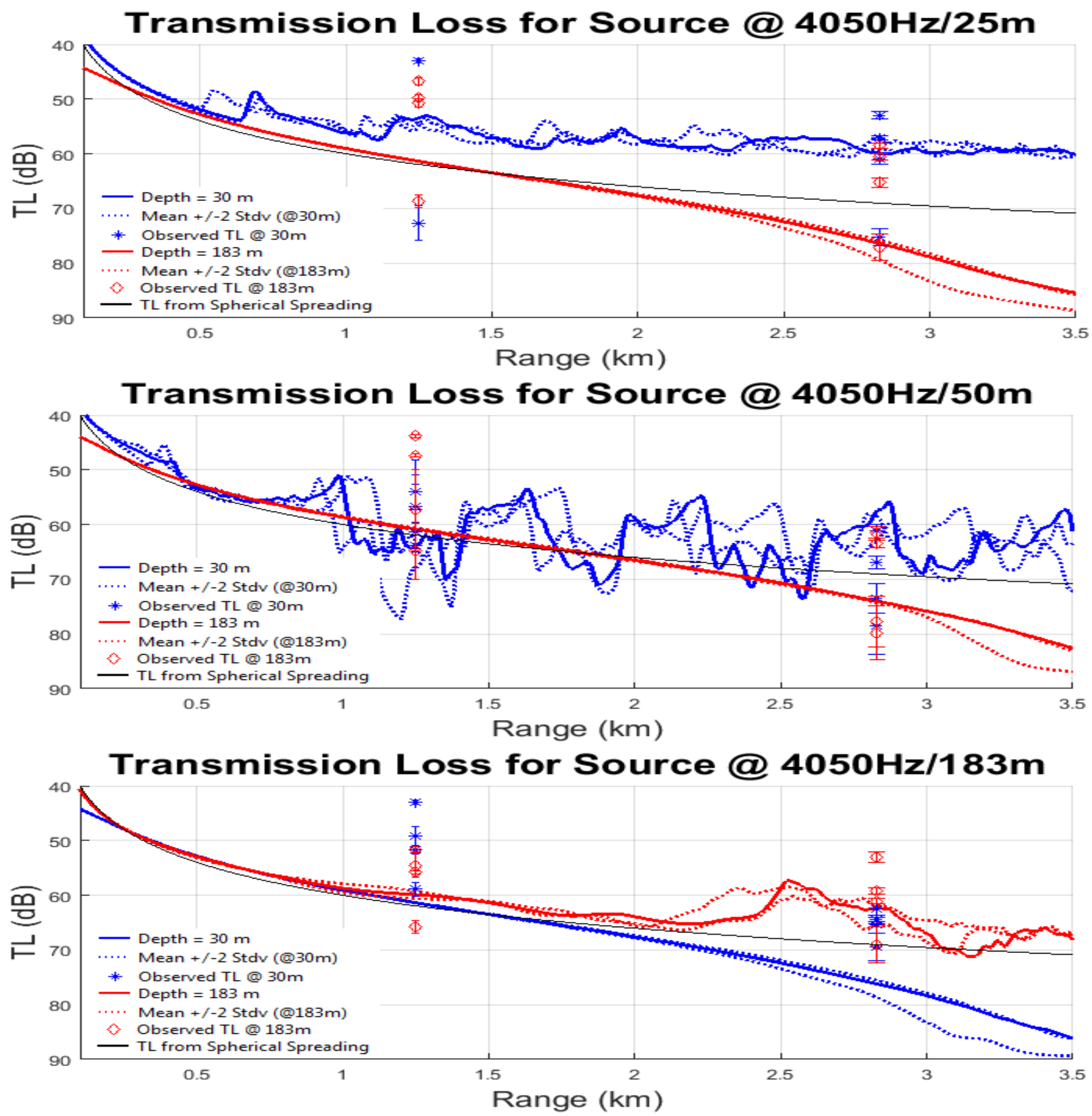
Transmission Loss for 950 Hz

Figure 12. Comparison of Observed vs. Modeled Transmission Loss for 950 Hz Signals.



Transmission Loss for 2800 Hz

Figure 13. Comparison of Observed vs. Modeled Transmission Loss for 2800 Hz Signals.



Transmission Loss for 4050 Hz

Figure 14. Comparison of Observed vs. Modeled Transmission Loss for 4050 Hz Signals.

V. DISCUSSION

A. SOUND SPEED PROFILES AND MODELING

The seven sound speed profiles obtained at Camp Sargo revealed a very consistent general profile over each of the trials and over the total distance covered. As expected, the deeper portions of the sound speed profile, greater than about 200 meters, was upward refracting. The sound speed peak at 80 meters was consistently present, and has a pronounced effect on upper column acoustic propagation. The sound speed peak provided two major contributions to the variability observed. The first, and most pronounced effect, was the resulting variability in acoustic propagation over relatively small depth changes. Observations over the water column from 25 meters to 75 meters yielded widely varying expected propagation characteristics and transmission loss. The second key observation was the amount of variability at 50 meters. While each of the CTD casts were considered very consistent, nearly all of the observed variability occurred at this depth. While less obvious through modeling, the variability in this region was likely a key factor in the variability of received acoustic levels and thus, transmission loss. A startling example was the amount of scattering observed at the source reference detector, shown in Figure 10. The variability is likely due to the interactions of two water masses interfacing at this location, resulting in some mechanism of mixing and turbulence. Further research in this area could yield a more satisfactory understanding of the observed phenomena.

B. TRANSMISSION LOSS

1. Observations

The transmission loss observations highlighted variability in two critical areas: between trial runs and during transmission periods. Variability of 10–20 decibels during and between transmissions was not uncommon, while some measurements were consistent within a few decibels. These results were unexpected, considering the perceived static configuration. The source to receiver ranges were considered fixed, as well as under-ice topography. Many surface effects were insulated by ice cover, and tidal

effects in the region are considered mild. The observations were taken over a short time period, approximately 18 hours, and geographical shift was limited to ice floe drift of no more than 30 kilometers, which should result in negligible changes in geophysical characteristics and bottom depth. The most common configurations resulting in high variability were source-receiver combinations across the sound speed peak at 80 meters and during source transmission at 50 meters.

2. Potential Sources of Variability

The transmission loss variability at the depths and ranges observed is likely related to the observed sound speed variability at 50 meters. A 1967 investigation into Arctic scattering layers using a 100 kilohertz sounder revealed undulations attributed to internal waves at 50 meters. While believed not typical of average conditions, the phenomenon had a distinct impact on scattering relationships (Hunkins 1971). It is possible that the layer observed nearly 50 years ago was not anomalous, and the variability observed in this series of observations was a result of the same mechanism. At a minimum, it is acknowledged that internal waves have been observed at the same depth in the same water mass in the past.

Internal waves occurring at the interface of two water masses, such as surface and Pacific layers, would result in varying degrees of turbulence also influenced by shear. While ray theory tells us that the acoustic signal is only sensitive to internal waves whose crests are aligned with the unperturbed ray, the occurrence of turbulence and mixing could result in turbulent “spicy” patches of water and salt fingering (Colosi 2016). Non-uniformities in water mass composition result in inhomogeneities of temperature and salinity, which characterize the thermal microstructure of the path from source to receiver. These characteristics are typically not of concern for long range and low frequency analysis, but may play an important function in the observations obtained in this configuration. The key idea is that temperature inhomogeneities cause the index of refraction to reside in a state of turbulent motion, resulting in acoustic propagation to occur over several paths and exhibit fluctuating signals at the receiver (Urick 1983). There is much room for further investigation into the specific mechanisms affecting the

observed variability. However, the amount of variability and attenuation observed at the reference detector located only 5 meters below the source clearly indicate that significant scattering mechanisms are occurring at a depth of 50 meters.

C. OBSERVED VS. MODELED TRANSMISSION LOSS

1. Representing Variability

The direct comparison of observed transmission loss to the models attempted to reasonably account for sound speed variability and the variability in received signals. The modeled data includes curves taking into account sound speed variability, indicating expected values within two standard deviations. The transmission loss observations include 1-standard deviation error bars to indicate variability during reception. However, in most cases, the models do not reliably represent the values observed in reality.

2. Observation/Model Mismatch

There is no immediately apparent pattern to the discontinuity between modeled and observed transmission loss. In some cases, the modeled values are greater than observed, and in others they are below. The 950 hertz/25 meter transmissions were the most accurately modeled configuration, and the receptions observed in this configuration appear to be minimally affected by variability. In some cases, the modeled variability appears to predict some magnitude of observed variability at both near and far VLAs, such as the 2800 hertz/183 meter source configuration, However, at the 2800 hertz/50 meter configuration, the model failed to predict the observed variability for the 183 m receiver on VLA2. It is worth noting that the observations in the 950 hertz/183 meter configuration appear to fit the spherical spreading curve better than the transmission loss models. The modeling does appear to capture some acoustic variability with the source-receiver combination of 50 meters and 30 meters near the sound speed variability peak at 50 meters depth, which are indicated by the blue lines in Figures 12–14. However, the models were generally not a reliable predictor of actual transmission loss and did not consistently predict variability in measurements.

3. Potential Causes of Mismatch

There are several potential causes for mismatch between modeled and observed transmission loss values. On predicting variability, the model accounted for the mean sound speed profile and identified 2 standard deviations above and below the mean. While this method did attempt to indicate expected variability, it does not account for the anticipated effects from turbulence and mixing at 80 meters, which is likely a significant factor. Additionally, water-ice interface scattering effects are not accurately represented, which would affect those sound rays downstream of a surface reflection. Inaccurately modeled scattering could also lead to a bias in the modeled results due to consistently over or under-estimating the transmission loss over the same patch of ice. A more comprehensive model would take into account inputs for turbulence and variability, as well as ice modeling data for reflectivity and under-ice topography.

VI. CONCLUSION

A. OVERVIEW

ICEX-16 offered a terrific opportunity to explore short range acoustic propagation under Arctic ice cover. Seven sound speed profiles were obtained, evaluated, and used to model ray theory and expected transmission loss. Recorded signals were analyzed for the source projector at Camp Sargo and the two VLAs located at distances of 1.25 kilometers and 2.83 kilometers away. Transmission loss was calculated for source-receiver combinations above, below, and across the sound speed peak at 80 meters' depth.

Key findings were the types and magnitudes of observed variability in measured recordings. Nearly all variability associated with the sound speed profiles occurred at 50 meters. Additionally, the source reference detector indicated unexpectedly high scattering and attenuation when transmitting at 50 meters. Signals received at the VLAs identified up to 20 decibels of variability during transmission periods as well as between trial runs. A final comparison of observed transmission loss to simulations yielded numerous inconsistencies with expected values to reality.

B. TACTICAL IMPLICATIONS

A discussion on the tactical implications assessed from the processed data is particularly useful from the perspective of a decision maker onboard a submarine due to the unique nature of under-ice passage. The first consideration is the information made readily available to the tactician. The database-provided sound speed profile shown in Figure 1 is woefully inadequate in representing the commonly observed sound speed peak at 80 meters. Unable to download satellite data through the ice, a first hurdle would be obtaining a correct SSP, which involves deploying an SSXBT, putting transient noise in the water, and thereby giving away the submarine's position. With an accurate understanding of the sound speed profile, the tactical decision maker could then identify the surface sound channel and the channel at approximately 200 meters. If the mission were to evade detection, the submarine would assess the depth at which the adversary would most likely be searching, and then position itself in the opposite layer. If the

mission involved searching for another contact, the submarine would likely position itself in the upper sound channel and attempt to place a line array in the lower channel in order to search both regions of the water column at the same time. However, understanding the sound speed and transmission loss variability should result in more frequent evaluations of expected gain and loss ranges, and could impact the tactical methods employed.

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